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# Small-scale household biogas digesters: An option for global warming mitigation or a potential climate bomb?

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ABSTRACT

There are a number of advantages to small-scale biogas production on farms, including savings on firewood or fossil fuels and reductions in odour and greenhouse gas emissions. For these reasons, governments and development aid agencies have supported the installation of biogas digesters. However, biogas digesters are often poorly managed and there is a lack of proper distribution systems for biogas. This results in methane being released inadvertently through leaks in digesters and tubing, and intentionally when production exceeds demand. As methane has a global warming potential 25 times greater than that of carbon dioxide, this compromises the environmental advantages of digesters. Calculations performed in this paper indicate that the break-even point at which the released methane has as great an impact on global warming as the fuel that has been replaced occurs when between 3% and 51% of the produced biogas is released, depending on the type of fuel that has been replaced. The limited information available as regards methane leaking from small-scale biogas digesters in developing countries indicates that emissions may be as high as 40%. With the best estimates of global numbers of small-scale digesters and their biogas production, this corresponds to methane losses of 4.5 Tg yr$^{-1}$ or about 1% of global emissions or 10% as much as emissions from rice production. Further poliferation of small-scale digesters could therefore contribute significantly to global emissions of methane. It is therefore important that governments and development aid agencies place stricter requirements on digester maintenance and biogas handling before incentives are created and legislation introduced for the installation of small-scale biogas digesters.



**Contents**



## 1. Introduction

Digestion of animal manure and human excreta in simple biogas digesters, is recommended as a way of managing manure

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on smallholder farms [1,2]. Biogas production reduces the need for fossil fuels and firewood, creates jobs, reduces odour and produces less indoor smoke than the other fuel types used in developing countries [3–5]. Due to these beneficial effects, small-scale biogas digesters have been widely promoted and supported financially by governments and development aid donors in large parts of Asia, including China, India, Vietnam, Bangladesh, Tibet and Pakistan [6,7].

An important additional advantage of small-scale biogas production, and one of the main objectives of government support for an increasing number of digesters in Asia, is that, when correctly managed, this technology is a cost-effective method of reducing greenhouse gas (GHG) emissions from animal manure [8]. It achieves this partly by providing fuel that can replace other fuels of fossil origin, and partly by reducing the GHG released along the entire animal manure management chain from animal to end-use on fields or in fish ponds. The savings have been calculated in assessments during several studies of digesters in China [3,9], India [10] and South America [11]. However, the advantages of biogas digesters may not be as great as they initially appear because the digesters release methane ($CH_4$) through leaks as well as from the inlets and outlets [12–14]. In many areas, intentional releases of surplus biogas may also be significant [15,16].

This paper reviews the deployment of small-scale biogas digesters in developing countries with a special focus on the possible sources of greenhouse gases associated with them. The objectives are the following: 1) to perform a break-even analysis that estimates the amount of $CH_4$ that can be lost from the digesters before the impact in terms of global warming cancels out the savings from reduced traditional fuel combustion, and 2) to estimate realistic losses of $CH_4$ from household digesters to establish whether they are likely to be above or below the break-even point. The loss of $CH_4$ is compared with emissions of $CH_4$ from other sources in order to determine the significance on a global scale and to see whether the proliferation of biogas digesters is a potential climate bomb.

## 2. Numbers, types and production of small-scale household biogas digesters

The history and development of household digesters in developing countries have been reviewed several times in recent years [17,18]. Approximately 35 million small-scale household biogas digesters have been constructed to date in developing countries, mainly in China and India but also significant numbers in other countries (Table 1). China has plans to increase the number of household digesters to 80 million by 2020 and India is also planning to increase the number of digesters as part of its ambitious plans for renewable energy [19,20]. Household digesters are also promoted by developing aid organisations in many parts of Asia [7]. Most small-scale biogas digesters are constructed below ground and the biogas is mainly used for cooking (Fig. 1).

**Table 1**
Number of biogas digesters in developing countries.

| Country and year of biogas statistics | Number of biogas digesters | References |
|---|---|---|
| China, 2010 | $3.1 \times 10^7$ | [20] |
| India, 2006 | $3.9 \times 10^6$ | [21] |
| Tibet, 2009 | $2.5 \times 10^5$ | [22] |
| Vietnam, 2012 | $2.0 \times 10^5$ | [16] |
| Bangladesh, 2010 | $6.0 \times 10^4$ | [23] |
| Africa, 2009 | Few[a] | [24,25] |
| Peru, 2010 | Few[a] | [26] |

[a] Only a small number of digesters are said to be in operation here.



**Fig. 1.** Picture of a typical cooking stove using biogas and the top of a biogas digester with an outlet for biogas.

There are two basic biogas digester designs used on small rural farms, the dome digester and the floating drum digester (Fig. 2, [18]). In the dome digester, manure is added through an inlet to a large dome that is typically 2–10 $m^3$ in size. Anaerobic microorganisms in the dome convert the dry matter in the manure into $CH_4$ and carbon dioxide ($CO_2$). Biogas accumulates, gradually increasing the pressure in the headspace above the manure. This pressure increase displaces manure from the dome until some of the gas is consumed. Digested manure is removed through a chamber connected by a tube to an opening below the manure surface in the dome. Biogas can be tapped from the headspace through a tube. In the floating drum digester, the biogas is contained in a drum floating on the manure being digested. This means that the weight of the drum which creates the pressure is constant, while the volume of gas varies.

The production of biogas depends on feedstock, residence time, and temperature. The rural household biogas digesters in China are mainly fixed dome digesters and are operated using pig manure. Digester size is generally between 6 and 10 $m^3$ [4,20]. Jiang et al. [20] estimated that rural biogas digesters produce between 0.1 and 0.3 $m^3$ gas per $m^3$ of digester volume per day. This means that digesters in China on average produce around 2.4 $m^3\ day^{-1}$ or 880 $m^3\ yr^{-1}$.

The digesters used in India are generally floating drum digesters and are smaller than those in China, ranging between 2.5 and 5 $m^3$ in size [18]. In India, cattle and horse manure is used as substrates. The biogas production per kg of mixed wet manure from cattle and horses is in the range of 21.9–29.5 L [27], corresponding to the production of around 0.3 $m^3$ biogas per $m^3$ of digester per day. This results in a production of around 1 $m^3\ day^{-1}$ or 380 $m^3\ yr^{-1}$.

## 3. Use of biogas and replacement of other fuels

The biogas produced in rural areas is mainly used for cooking, heating and lighting and therefore replaces energy sources commonly used for these purposes in the household, such as wood, dried dung, coal or liquid petroleum gas (LPG, mainly propane). As these fuels have different impacts on the environment, it is important to know which fuels the biogas actually replaces.

In China, biogas is mainly used for cooking, primarily replacing biomass and coal [3]. In rural China, biomass and coal cover 67% of the energy used for cooking and heating, of which straw contributes 26–33%, firewood 14–21% and coal 27–34% [4,28]. The fuel replaced by biogas energy is straw (33%), firewood (24%), coal

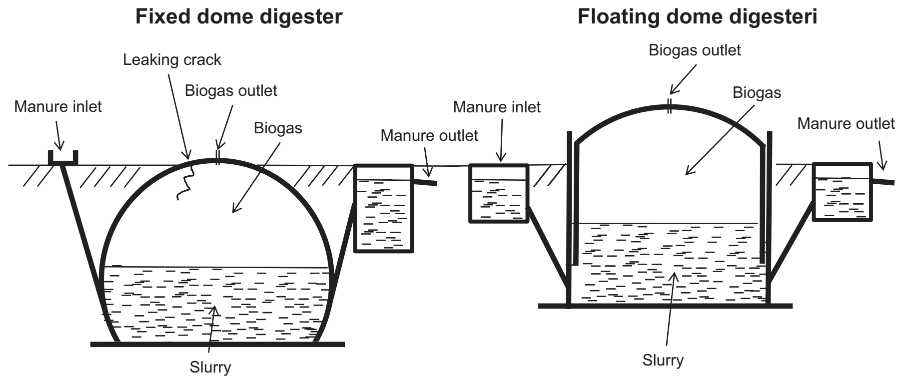



**Fig. 2.** Left: dome digester; right: floating drum digester.

(32%), electricity (8%), refined oil (2%), LPG (1%), natural gas ( < 1%) and coal gas ( < 1%) [3].

In India, the biogas produced in rural areas mainly replaces biomass energy [21]. In 2001, biomass covered 72% of the energy used in households, of which firewood contributed 52%, crop residues 10% and cow dung 10% [21,29]. Within the last decade, LPG consumption has increased in India while the use of dung has significantly decreased, a trend reflecting the increased wealth of small farm households.

## 4. Break-even analysis of biogas emissions

Since $CH_4$ is a potent greenhouse gas, emissions caused by biogas leaks and intentional releases pose a major problem that threatens to cancel out the advantages of biogas digesters in terms of mitigating global warming.

When assessing the effects of biogas production and biogas losses to the atmosphere, it is important to account for the energy source replaced by the biogas. Therefore the global warming potentials due to $CH_4$ emissions from biogas digesters and $CO_2$, $CH_4$, $N_2O$, and CO emissions during combustion of the biogas were compared with the emissions of these gases during combustion of the fuels that are being replaced. The aim of the analysis was to find the break-even point at which $CH_4$ emissions from biogas production give rise to the same global warming potential as the fuels being replaced by the biogas.

The $CO_2$ emitted during the combustion of biogenic fuels such as wood and crop residues was recently fixed by photosynthesis when the plants were growing. These fuels are therefore sometimes considered to be $CO_2$ neutral. This is also the case for manure-derived biogas, because the carbon in the gas originates from the feed eaten by the animals. However, in addition to $CO_2$, small quantities of $CH_4$, $N_2O$, and CO are released during the combustion of fuels, all of which have climate warming potential [3,30]. The potential emissions of these gases when delivering 1 MJ of thermal energy to a pot of water are shown in Table 2.

If a significant fraction of the produced gas is lost, then a larger amount of biogas needs to be produced to satisfy the same energy demand as for a system without leaks. The amount of $CH_4$ that needs to be produced per unit of energy delivered to heat water can be calculated using the following equation:

$$M_p(f_l) = \frac{1}{59(\text{MJ kg}^{-1})0.57(1-f_l)}$$

where $f_l$ is the fraction of biogas lost either through leaking or intentional release, 59 MJ kg$^{-1}$ is the energy content of $CH_4$ and 0.57 is the efficiency of the stove running on biogas [29].

**Table 2**
Energy content of fuels (lower heating value) and GHG emissions during combustion of different fuels in ordinary household stoves used in developing countries for each fuel type [3,18,19,32].

| | Energy content of fuel | Gas emission per MJ delivered energy | | | |
|---|---|---|---|---|---|
| | (MJ kg$^{-1}$) | g $CO_2$ | mg $CH_4$ | g CO | mg $N_2O$ |
| Biogas | 17.7 | 81.5 | 57 | 0.11 | 5.4 |
| Coal | 24.9 | 682 | 1300 | 26.2 | 1.4 |
| LPG | 45.8 | 139 | 8.9 | 0.82 | 6.0 |
| Wood | | 532 | 600 | 14 | 4.3 |
| Dung | | 885 | 7100 | 39 | 270 |

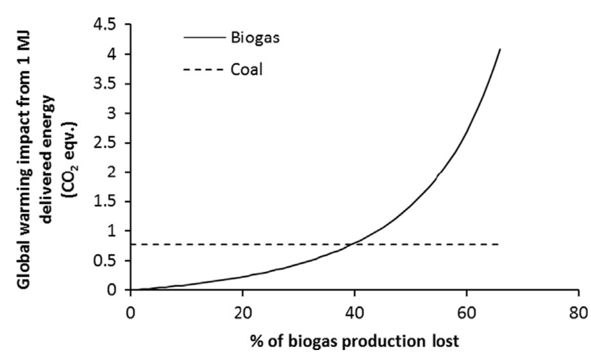



**Fig. 3.** Global warming impact of $CH_4$ emissions from biogas production. The global warming potential is given in $CO_2$ equivalents of $CO_2$, CO, $N_2O$ and $CH_4$ produced when heating water by 1 MJ.

Subsequently the amount of lost $CH_4$ per unit of energy delivered is as follows:

$$M_l(f_l) = f_l M_p(f_l)$$

Finally the global warming impact potential per unit of energy delivered can be calculated as follows:

$$IPB_{GW}(f_l) = M_l(f_l)CF_{CH_4} + ECB_{CH_4}CF_{CH_4} + ECB_{N_2O}CF_{N_2O} + ECB_{CO_2}CF_{CO_2} + ECB_{CO}CF_{CO}$$

where $CF$ is the characterisation factor for $CH_4$, $N_2O$, CO and $CO_2$ which are taken to be 25 g $CO_2$ eqv. g$^{-1}$ for $CH_4$, 1.9 g $CO_2$ eqv. g$^{-1}$ for CO, and 295 g $CO_2$ eqv. g$^{-1}$ for $N_2O$ [31], and $ECB$ is emissions during the combustion of biogas which are given in Table 2. A similar equation can used to calculate the impact potential of emissions from the replaced fuels, which are not associated with the same losses of $CH_4$ during production:

$$IPR_{GW} = ECR_{CH_4}CF_{CH_4} + ECR_{N_2O}CF_{N_2O} + ECR_{CO_2}CF_{CO_2} + ECR_{CO}CF_{CO}$$

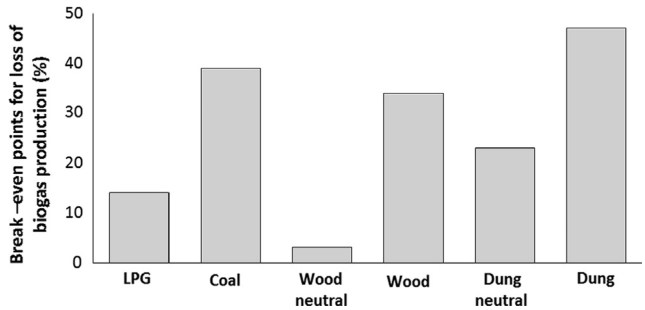



**Fig. 4.** Break-even point for loss of biogas where the loss of $CH_4$ in the biogas gives rise to the same global warming potential as that of the fuel substituted by the biogas.

where *ECR* is the emissions during the combustion of the replaced fuels which are also given in Table 2.

Fig. 3 compares the impacts of the biogas with those associated with the use of coal as a function of the fraction of produced $CH_4$ that is lost during biogas production. It can be seen from the diagram that the break-even point for the climate effect of replacing coal with biogas occurs when 51% of the produced biogas is lost.

The break-even point for global warming potential was determined in the same way when biogas replaced dung, firewood, coal and LPG (Fig. 4). While the $CO_2$ emitted from the combustion of wood and dung is often considered to be $CO_2$ neutral, wood is harvested unsustainably in many parts of the world and it may therefore not be realistic to assume that the forest will grow back within a reasonable period. Therefore, two calculations were performed: one in which wood was considered to be $CO_2$ neutral and one in which it was not. From Fig. 4, it is evident that biogas losses can be substantial before they match the impact of some fuels. For dung, the break-even point occurred at 28% of the biogas produced. For LPG, the break-even point was considerably lower at around 16% of biogas losses. Meanwhile for the wood considered to be $CO_2$ neutral, losses of biogas had to be very small (around 3%) to reach the break-even point, whereas it could be considerably greater (around 44%) when it was not considered $CO_2$ neutral.

Biomass and coal stoves have substantially lower thermal efficiency than those of stoves using liquid and gaseous fuel. As a result, the $CO_2$ and GHG emissions per unit of energy delivered are considerably greater for biomass and coal stoves than for gas and liquid fuel stoves, as is their effect on indoor air quality. Households therefore tend to omit the poor and polluting energy sources if they can afford to buy LPG. Thus, the choice of energy sources can be ranked from lower- to higher-quality fuels, *i.e.* emissions decrease and thermal efficiency increases in the following order: dung, crop residues, wood, coal, kerosene and LPG [32]. In Asia, households move up the energy ladder for cooking as their level of income improves, a trend that improves indoor air quality, energy use efficiency and convenience [30]. As can be seen from Fig. 4, it is also evident that the high-quality fuels have the lowest global warming impacts, at least if wood is not considered to be $CO_2$ neutral.

## 5. How great a fraction of biogas is likely to be lost?

Based on the information presented above on the break-even points for biogas losses depending on the fuel type replaced, it is important to determine how much of the biogas produced is likely to be lost under actual biogas digester conditions.

Unfortunately, very little information is available about $CH_4$ losses from small-scale biogas digesters in developing countries. However, there are several known sources of such losses. In the case of dome digesters, the inlet and outlet are open and any gas produced in these is lost to the atmosphere. In floating drum digesters, there is a volume of manure around the drum and any gas produced in this volume is also released to the atmosphere in addition to the emissions from the inlet and outlet (Fig. 2). Furthermore, the digester body and tubing may have cracks and may potentially leak. Finally, whenever production exceeds consumption, biogas accumulates in the digester and has to be disposed of in some way. This can be done by either flaring or direct release. This last option can involve the release of large amounts of $CH_4$ to the atmosphere.

Regarding the emissions from digester inlets and outlets, Khoiyangbam et al. [13] calculated annual emissions from 2-$m^3$ fixed dome biogas digesters to be 53.2 kg $CH_4$ in regions with a warm climate and 22.3 kg $CH_4$ in colder climates. This calculation was based on the assumed production of 0.4 $m^3$ biogas per $m^3$ of digester per day. Assuming this rate of production and half that amount in the digester at high altitudes, this equates to losses of 17% and 14% of the biogas produced respectively. Khoiyangbam et al. [12] estimated annual losses of 22– 98 kg $CH_4$ from the inlets and outlets of 3–9 $m^3$ floating drum digesters. Using the same assumptions regarding production, this equates to losses of 5–8% of the $CH_4$ produced.

A study in China concluded that fugitive $CH_4$ emissions from leaks are negligible because the digesters that were used for the measurements were well maintained [33]. However, fugitive emissions even from well-maintained biogas digesters have been estimated to be as high as 3.1% of $CH_4$ production under normal operation [34]. In addition to this, most biogas digesters are not likely to be well maintained. A recent study found that a lack of skilled labour in rural regions may lead to inappropriate handling of digesters [20]. Furthermore, Chen et al. [4] estimated that only 60% of digesters in China were operating efficiently. This impression is supported by surveys from Vietnam, which found broken dome digester caps and gas valves that were not airtight, resulting in gas leaking into the atmosphere [16]. A study from Pakistan found biogas digesters with persistent leakage and seepage problems from cracks in the walls caused by temperature variations [14]. Based on this, it can be assumed that losses through leaks may be substantial – up to 10% of the biogas produced on average or even more.

A potentially greater source of GHG from digesters comes from the intentional release of excess biogas [15,16]. Almost no information about this source of GHG is available in literature, although the intentional release of biogas has been identified as a problem for small biogas plants in Thailand, where release and flaring were estimated to account for 15% of the gas produced [35]. An unpublished survey from four different provinces (Binh Dinh, Dong Nai, Gia Lai and Tra Vinh) in southern Vietnam [36] showed that 140 of 216 households (65%) with a biogas digester had excess biogas that they could not use in the summer. Of these 140 farms with excess biogas, 68 (48.6%) released it directly into the atmosphere, while the rest either gave or sold it to a neighbour or burned it. Assuming there are no differences in the amount of excess gas on the farms that released biogas or used it for other purposes, the proportion of excess biogas that was released was also 48.6%. In the same survey, for 93 of the 216 farms (43%) using LPG before they installed biogas digesters, farmers indicated that they saved on average 8.97 kg of LPG gas because of the biogas they consumed. This saving in LPG corresponds to 21.7 kg or 17.9 $m^3$ of biogas, assuming an energy content of 45.8 MJ $kg^{-1}$ for LPG and 17.7 MJ $kg^{-1}$ for biogas and a thermal efficiency for LPG and biogas stoves of 53.6% and 57.4% respectively [29]. The average size of biogas digester in the survey was 12.03 $m^3$. Assuming average production of 0.2 $m^3$ biogas per $m^3$ of digester and per day [20], production would be around 72 $m^3$ per month. This means

that only 24.7% of the biogas produced is used on the farm and 75.3% is excess. Since an estimated 48.6% of the excess is released directly, the proportion of the total biogas produced released directly to the environment is 36.6%. This figure is likely to be lower in winter, when production is lower and therefore the excess is smaller. In areas with colder climates and for those using smaller digesters and with fewer pigs, intentional release is likely to be much smaller.

Overall, total losses of $CH_4$ from biogas digesters may be as high as 40% of the amount produced if the emissions from the inlet and outlet, leaks and intentional releases are added together. This is probably a worst-case estimate, but locally the losses are likely to vary from considerably below this figure to considerably above it.

## 6. How much $CH_4$ could potentially be emitted from household digesters globally?

Using the above figures, it is possible to estimate the potential release from small-scale household biogas digesters around the world. With around 31 million digesters in China and an average production of 880 $m^3\,yr^{-1}$ from each of these digesters, and around 4 million digesters in the rest of the world with a production of 380 $m^3\,yr^{-1}$, this corresponds to a total production from all the digesters of around $2.8\times10^{10}$ $m^3\,yr^{-1}$. Assuming a $CH_4$ concentration of 60%, this corresponds to $CH_4$ production of approximately 11 Tg $yr^{-1}$. If the emissions of $CH_4$ are 40% as estimated above as a maximum value, this corresponds to 4.5 Tg $yr^{-1}$. This constitutes approximately 1% of global emissions which have been estimated to be around 550 Tg $yr^{-1}$, or about 10% as great as the emissions associated with rice production, 3% as great as the emissions associated with enteric fermentation or 13% as great as the emissions caused by termites [37,38]. With a projected increase in numbers to around 100 million by 2020, emissions could be as high as 12 Tg $yr^{-1}$, which would correspond to more than 2% of global emissions. As $CH_4$ is the most important greenhouse gas after $CO_2$, contributing around 0.7 W $m^{-2}$ of a total radiative forcing of around 2.77 W $m^{-2}$ [38], this is not insignificant. Considering that even 100 million biogas digesters is a small number in comparison with the potential number that could be installed worldwide, uncontrolled future proliferation without some sort of mechanism to ensure correct operation could constitute a virtual climate bomb.

## 7. How can the correct operation of household biogas digesters be ensured?

Small-scale biogas digesters can be a very useful manure management tool and may help reduce global warming impacts if used appropriately. However, the analysis above shows that when used inappropriately, they can result in large emissions of GHGs. Thus, it is absolutely crucial to ensure they are operated appropriately.

From the analysis above, it appears that the greatest problem is the intentional release of biogas. Deliberate releases are partly due to the rapid expansion of Asian livestock production, with more specialised and intensive production. The specialised farms use commercial feed instead of home-grown feed which was often cooked using biogas on the farm. Thus the biogas digesters receive more manure and produce more gas, while less gas is used for feed pre-treatment. Furthermore, specialised farms are often located far away from residential housing and therefore it is not convenient to use the gas in other households. Increased livestock production also reduces the retention time of biomass in the digesters, leading to enhanced $CH_4$ emissions from stored digestate [39], and in turn to further negative effects of the biogas digester on global warming.

A prerequisite for avoiding the intentional release of biogas and for the efficient use of biogas digesters in general is the reliability of the energy supply. It is important for the owner that gas production is reliable and relatively constant, so that consumption can be adjusted to avoid surplus production, making it worthwhile to maintain the digester and avoid leaks. An operational biogas storage bag made of flexible fabric material could significantly improve the efficiency and safety of the system. It could also allow fluctuations in the production and consumption of biogas and compensate for temperature-related changes in volume. One of the major problems affecting the reliability of biogas production is that seasonal temperature variations affect the production rate in non-insulated small-scale digesters. Hence, in winter, when demand for biogas is typically high, low temperatures limit production in many non-tropical areas. Around 60% of the heat loss occurs from the top of the digester [40]. A simple solution could therefore be to insulate the top of the digester with organic material, *e.g.* straw, turf or dry compost. This would reduce the influence of ambient air temperature variations, rendering the temperature of the buried digesters closer to the fairly constant soil temperature. Simple solar energy panels could also be used to supply heat to the digester in sunny regions. Alternatively, hot water heated by biogas could be circulated through the digester. However, in some areas with low winter temperatures, it may prove too difficult to make the digester work and the technology may not be applicable. Better predictions of gas production and techniques to align gas production and consumption have to be developed without sacrificing the simplicity of the technology, making it applicable in rural areas in developing countries. New designs must therefore not introduce too much complexity, increase costs or add demands on managers. It is therefore proposed that governments support research and development initiatives developing simple solutions to improve the biogas digester technology.

Another way of avoiding excess biogas being released into the environment is an efficient distribution system for the gas. Sharing with neighbours is an obvious choice, but has often proved difficult and is possible only in densely populated areas. Upgrading or purification of the gas and compression on flasks is expensive, but also provides an opportunity for owners to generate income [41]. Development of distribution systems should therefore be a key focus for future research and development.

## 8. Requirement for further knowledge and regulations

The simplified analysis conducted here is useful for illustrating the problems caused by leaks and the intentional release of biogas. However, it is evident that there is very limited knowledge about emissions from leaks and the intentional release of biogas from small-scale biogas digesters. It is therefore imperative to increase knowledge of this with empirical measurements from a large number of digesters from different countries. Furthermore, a more refined analysis is required that also includes emissions during the storage of manure and downstream emission, and emissions during the production of the replaced fuels. Nevertheless the analysis clearly illustrates that it is crucial that governments and development aid agencies institute requirements for digester maintenance and biogas handling before they support, create incentives for and introduce legislation concerning the installation of small-scale biogas digesters. Educating farmers about digester maintenance and operation could improve the production of biogas [4]. However, it is also likely that it could help farmers avoid $CH_4$ emissions from leaks and certainly from the intentional

release of biogas. The analysis shows that the environmental advantages of a digester depend on the fuel being replaced and this should therefore be considered before supporting the construction of a biogas digester. It is also important to assess whether there are likely to be large amounts of excess biogas and if there is a proper distribution system or system for getting rid of excess biogas. For example, it may not be feasible to flare large amounts of biogas in a residential neighbourhood and alternative ways of eliminating or utilising excess biogas should be devised before a biogas digester is supported in such an area.

## 9. Conclusions

The calculations presented here show that $CH_4$ emissions from the inlets and outlets of small-scale biogas digesters, from leaks and from intentional releases, are likely to be substantial because of poor maintenance and poor biogas handling. In many cases, the global warming impact of this $CH_4$ could be greater than the impacts avoided by the replacement of other fuels for cooking and other purposes. In particular, the observation that large amounts of biogas may be intentionally released when the production of biogas exceeds consumption is a cause for concern.

Small-scale biogas digesters can be a very useful manure management tool and may help reduce global warming impacts if used appropriately. However, if used inappropriately, their proliferation could constitute a virtual climate bomb. Therefore, it is crucial that development aid agencies and policy makers introduce requirements for digester maintenance and biogas handling before they support, create incentives for and introduce legislation about the installation of small-scale biogas digesters.

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